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Title: National Lightning Detection Network: Summary of Strike Peak Currents

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National Lightning Detection Network: Summary of Strike Peak Currents

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1 Introduction

Over the years 2006 through 2017, the National Lightning Detection Network (NLDN) measured about 880 million lightning ground strikes in the continental United States. About 5.5% of these strikes had positive initial peak current. We examine the extreme quantiles of positive and negative peak current. For example, the 99% quantile indicates that 99 out of 100 strokes are less than the quantile. Noting that the estimation of the 99% quantile, e.g., depends on the area and time period under consideration, we examined the effects of location and time period (both seasonally and yearly) on the determination of 99% quantiles. In the appendices, we detail the uncertainty quantification procedure and summarize strikes in January 2016.

2 Summary of peak current of all ground strikes

2.1 Quantiles

We determined the empirical quantiles of "extreme" values in peak strike currents that pass between cloud and ground. Due to the size of the dataset (approximately 500GB), we reduced the dataset by only reading in the approximately 6.6 million ground strikes with peak current greater than 100 kA or less than 50 kA. However, the quantiles reported are relative to the entire dataset.

The 99% quantile indicates that 99 out of 100 strokes (across the continental United States and years 2006 to 2017) are less than the quantile. Estimated quantiles across all years and the entire continental United States are given in Table 1. Uncertainties were determined by bootstrapping, and reflect uncertainty in quantile estimation and symmetric measurement errors (Idone et al., 1993; Cummins et al., 1998). To bound uncertainties, we assumed that peak current was accurate to 30%, and assumed that the measurement errors are log-normally distributed; see Appendix A for details of the bootstrapping procedure.

Histograms of stroke peak currents are given in Figure 1. Generally, positive strokes are more severe, but only at the extreme quantiles.

Table 1: Empirical quantiles for ground strike peak current (kA) based on NLDN data from 2006 through 2017, where the 99% qunatile of q denotes that 99% of strikes were below q, separated by positive and negative polarities.

Positive			Negative		
99%	99.9%	99.99%	99%	99.9%	99.99%
141.39 ± 0.12	245.15 ± 0.49	382.51 ± 2.07	90.55 ± 0.02	177.35 ± 0.1	281.15 ± 0.32

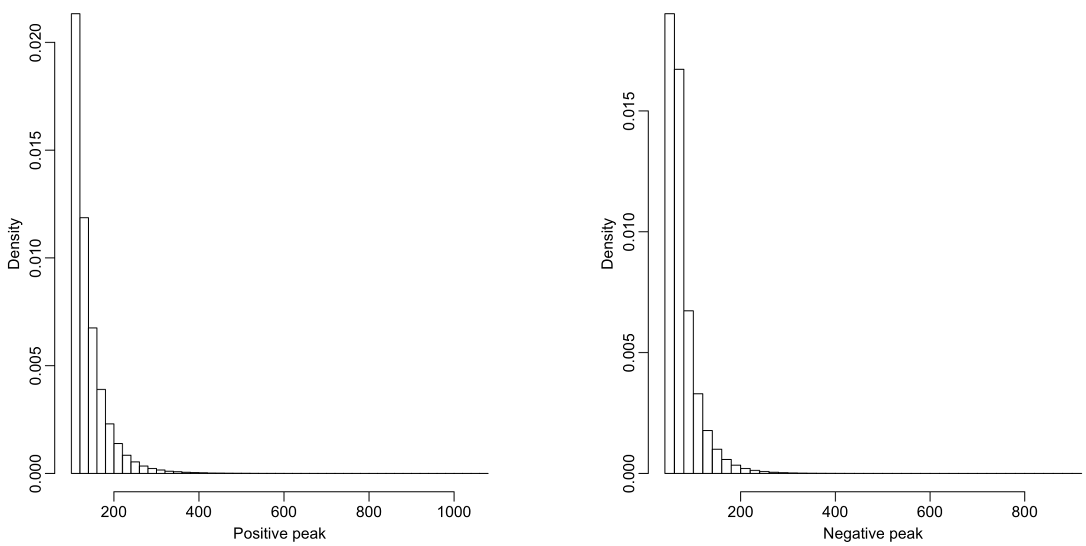


Figure 1: Distribution of peak currents (kA) over 100 kA, or less than -50 kA, observed by the NLDN from 2006 through 2017.

The yearly trends of quantiles are plotted in Figure 2. Notably, years 2016 and 2017 appear to have lower values for positive strikes. Conversely, negative strike quantiles appear to increase over time across the entire dataset.

2.2 Distributional forms

Some authors have claimed that the logarithm of peak stroke current (separated by positive and negative, at times) follow a log-normal distribution. If a random variable is log-normally distributed, then its logartithm is normally distributed. We examined the claim of log-normally distributed peak currents by reading a random subset of 10 million measured strokes, over all years and throughout the continental United States. The distributions of logarithms of peak currents are plotted in Figure 3.

The distributions are generally bell-shaped, yet, the Shapiro-Wilk test indicates that the distributions are significantly non-normal ($p < 0.0001$). However, we find that for sufficiently small sample sizes, such as $n \leq 1000$, there is not evidence of non-normality. The small sample sizes in previous datasets may thus explain the claim of log-normality.

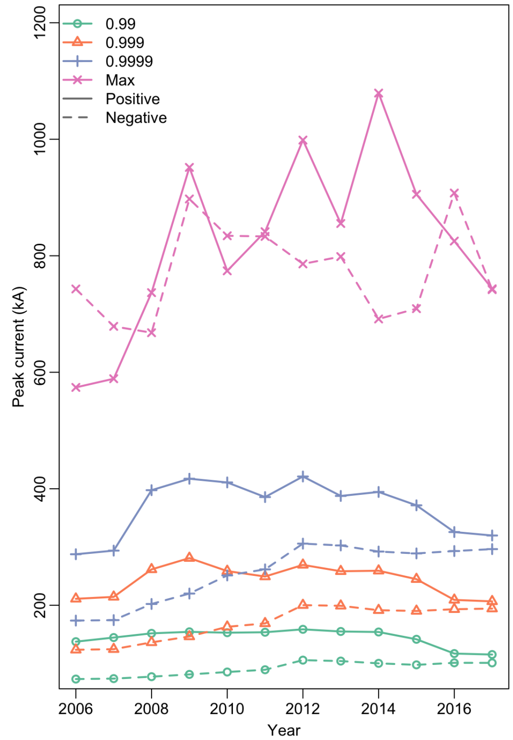


Figure 2: Yearly peak current (kA) quantiles observed by the NLDN from 2006 through 2017.

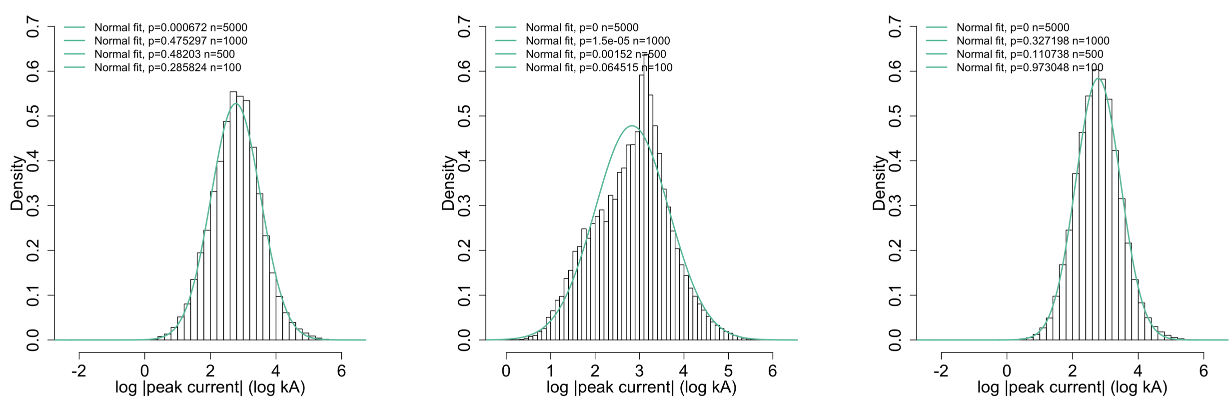
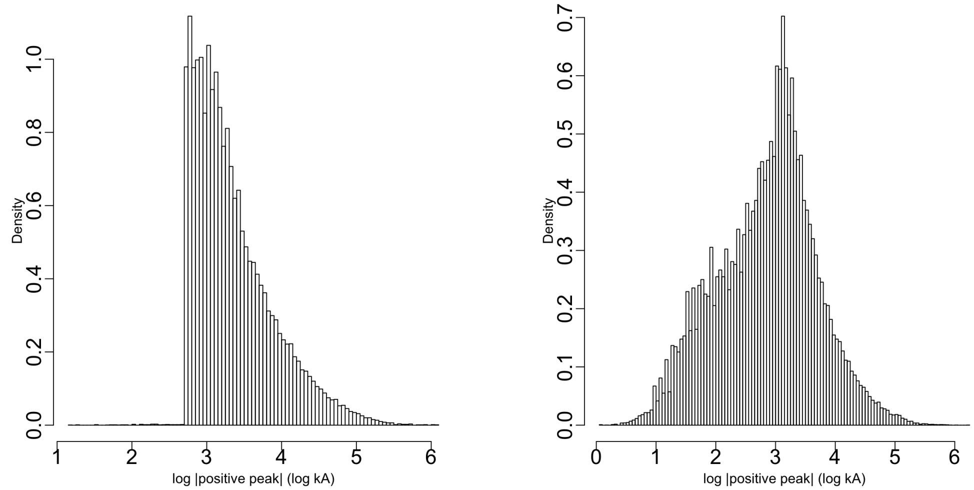


Figure 3: Distribution of log peak currents (log kA) observed by the NLDN from 2006 through 2017 (positive peaks are only 2016 and 2017). In the legend, p-values for the Shapiro-Wilk test are given with the subsample size.

2.3 Positive strike caveat

In the previous section, we only plotted positive strikes from 2016 and 2017. This is because, for years before 2016, there exists a cutoff of 15 kA below which no positive strikes are recorded (see Figure 4). Before 2016, the NLDN “classified all positive lightning events having peak currents less than +15 kA as cloud pulses" (Nag et al., 2016). This fact is likely the cause of the decrement in 99% quantiles in 2016 and 2017 in Figure 2. Furthermore, the quantiles in Table 1 for positive strikes may be slight overestimates.



2015 2016

Figure 4: Distribution of log peak currents (log kA) observed by the NLDN in 2015 and 2016.

3 Spatial variability of peak current

We plotted a random subset of strikes in 2017 that were over the 99% positive and negative quantiles (see Figure 5). We also include a random subset of strikes less than the 99% quantiles. There is clear spatial pattern, where there are many more "extreme" negative strikes in the southeast of the country, and even over the Gulf of Mexico and Atlantic Ocean. The north and center of the country is more likely to experience extreme positive strikes. Smaller strikes appear to follow locations of extreme strikes, with perhaps more concentration over land than extreme negative strikes.

We repeated the plot for 2017, for 2016, in Figure 6. We observed roughly the same trends as in 2017, with large negative strokes over the southeast and southeastern oceans, and large positive strokes over the northern center of the country. There do appear to be more large positive strokes in 2016 than 2017, indicated that spatial dependence may vary from year to year.

4 Temporal variability in peak current

There is clearly an annual trend in peak current (see Figure 2). We briefly investigate monthly trends in this section. Figures 7 and 8 show the spatial variation in number of extreme strikes in January and July, respectively, for random subsets of the NLDN data over all years. Generally, we can most likely conclude that there are many more strikes in

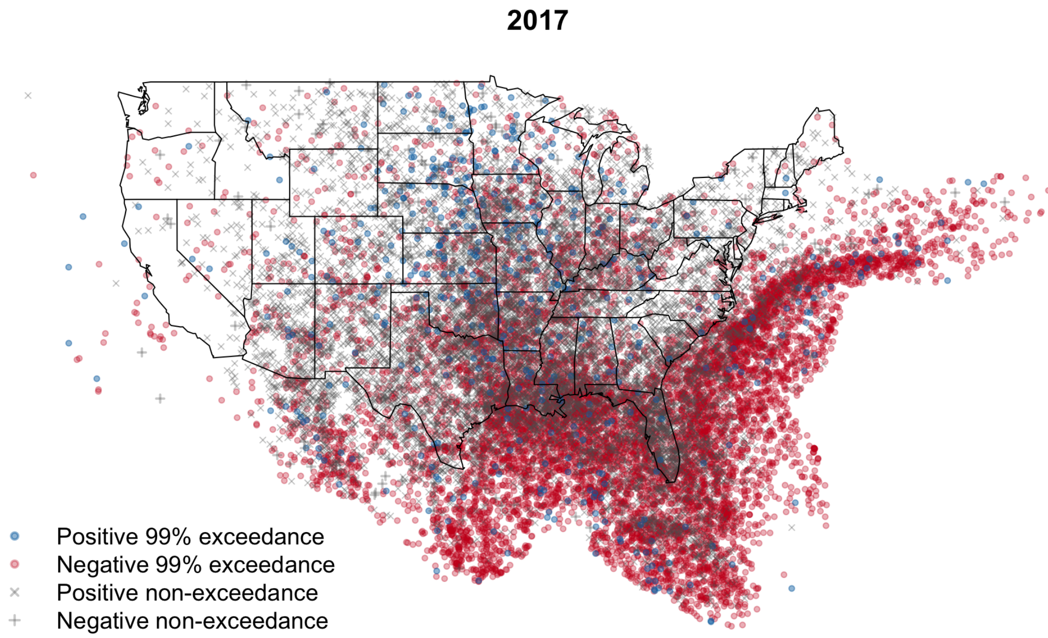


Figure 5: Measured positions of strikes greater than 99% quantiles in 2017.

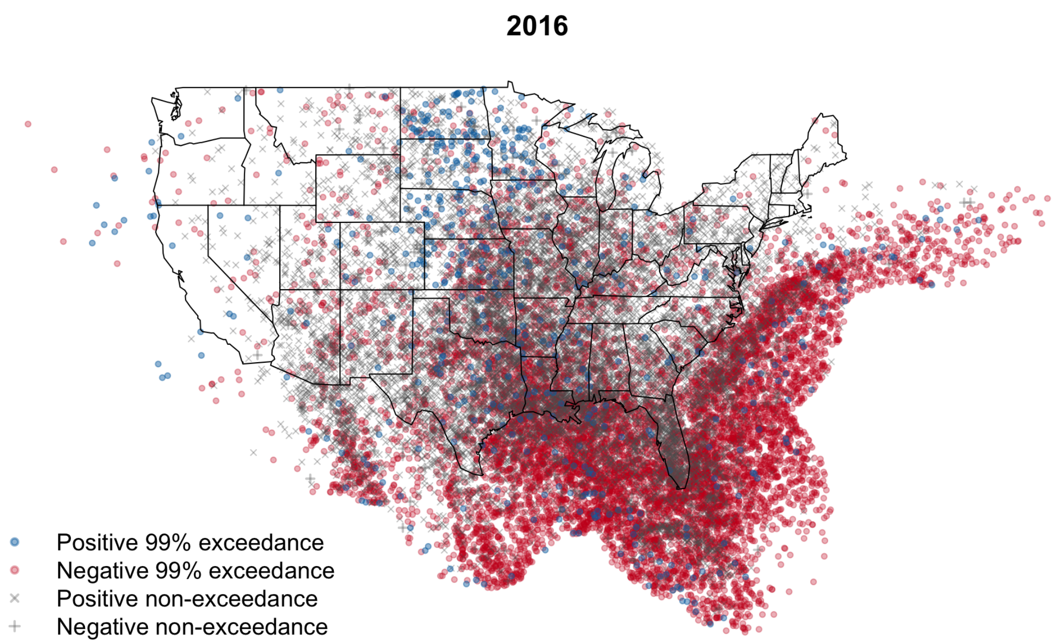


Figure 6: Measured positions of strikes greater than 99% quantiles in 2016.

warmer months than cooler months. Further, in cooler months, strikes are more concentrated in the southeastern continental US. However, Figure 9 indicates that cooler months actually have larger extreme peak currents.

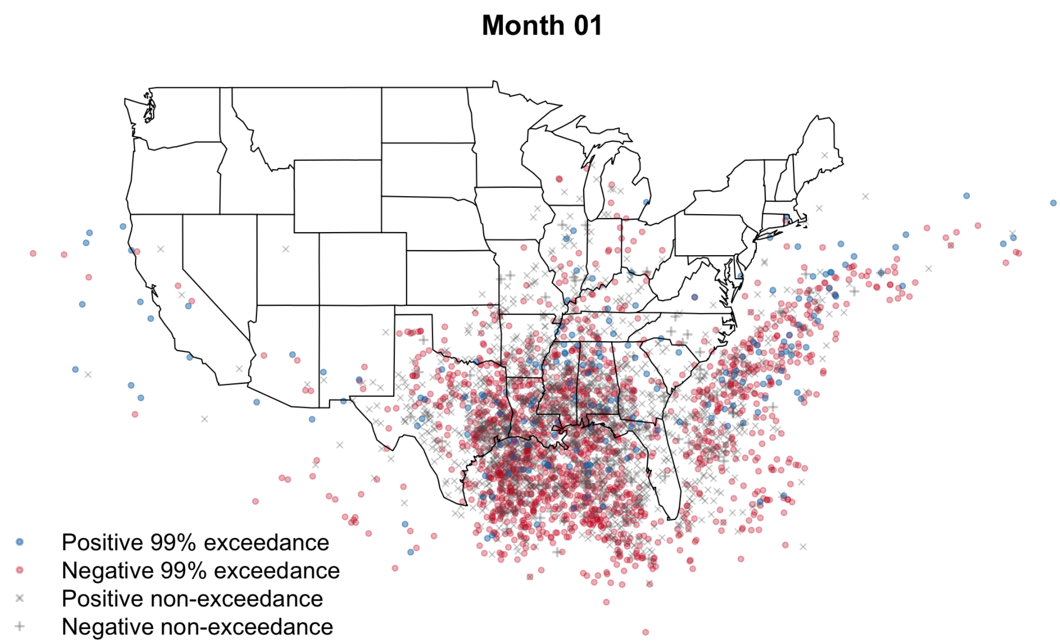


Figure 7: Measured positions of strikes greater than 99% quantiles in January.

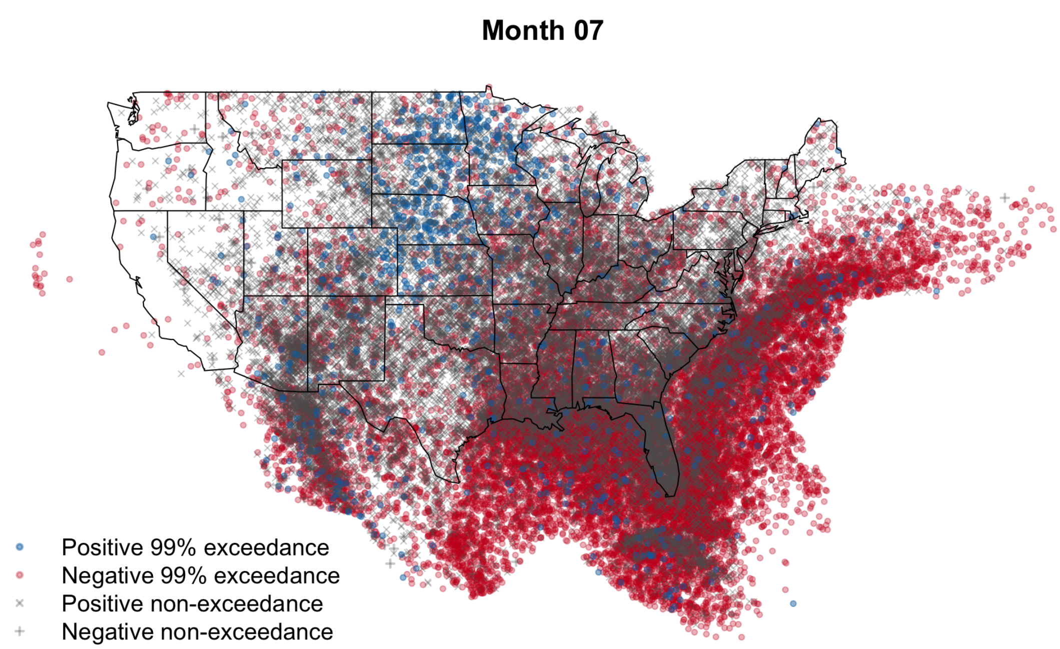


Figure 8: Measured positions of strikes greater than 99% quantiles in July.

5 Conclusion

We precisely determined the 99% quantile of peak positive and negative currents, which are about 140 kA and 91 kA, respectively. These quantiles are over a longer period of

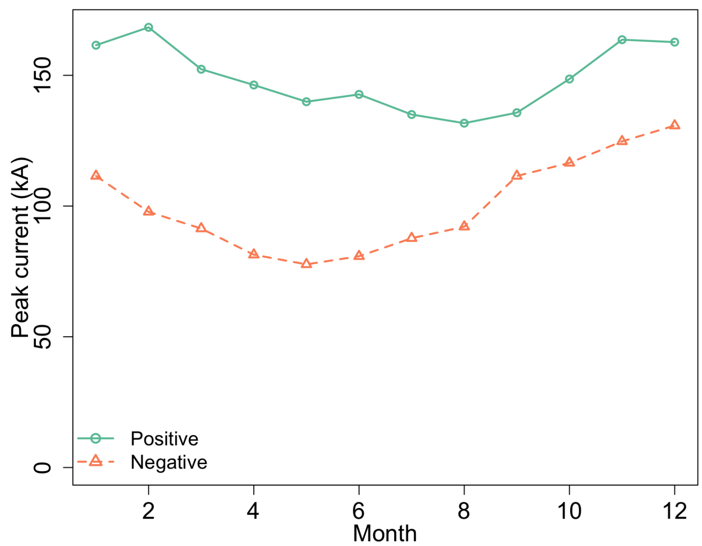


Figure 9: 99% quantiles for each month, across all years 2006 to 2017 of NLDN dataset.

time (12 years) and larger area (the entire continental US) than have typically been used to estimate quantiles of peak currents from lightning strikes. Previous studies (Fisher and Uman, 1989; Heidler et al., 2008; Uman et al., 2010) have reported 99% quantiles in the range of 200-500 kA and 100-200 kA for positive and negative peak currents, respectively. Our study suggests that these estimates are overestimates, and may be due to the smaller size of these data sets. Further, based on Berger (1975), peak current is highly correlated with other lightning parameters. For example, peak current was found to have correlation of 0.84 with discharge energy. As such, conservatism of standards on the part of peak current may suggest that other parameters, such as discharge energy, are similarly conservative. Similar investigation into other lightning parameters for large datasets, documenting strikes over broad areas and time periods, should be conducted to confirm and/or refine 99% quantiles of other parameters.

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A Uncertainty quantification

There are two possible sources of uncertainty: error in estimation of the 99% quantile of the true distribution (which cannot be directly measured), and measurement error of the peak current in the NLDN. In the former case, bootstrapping may be used to quantify the estimator uncertainty (Maritz and Jarrett, 1978). In addition, we incorporated the estimate of uncertainty due to measurement error into the bootstrapping procedure. Measurement error of the peak current by the NLDN has been quoted at 15% (Idone et al., 1993) and 20-30% (Cummins et al., 1998). We assume that the error distribution is symmetric (Idone et al., 1993) and log-normally distributed, with mean zero and standard deviation

$$\sigma = \frac{\log 1.30}{2}, \tag{1}$$

where $\log x$ denotes the natural logarithm of x. We use 30% measurement error to bound the effect of measurement uncertainty.

The bootstrap procedure is detailed as follows. For each of 10,000 iterations, we

1. Sample the number of strikes above 100 kA, $n_{over} \sim \mathrm{N}(np, np(1-p))$, where n is the total number of positive observations and p is the observed fraction of positive observations over 100 kA,
2. Resample n_{over} of the observed positive strikes above 100 kA, with replacement,
3. Add log-normal noise to the resampled positive strikes, $\log x_i = \log x_i + \epsilon_i$, where $\epsilon_i \sim \mathrm{N}(0, \sigma^2)$,
4. Compute and save the 99% quantile.

We do the same bootstrap procedure for negative strikes, where the threshold is -50 kA (rather than 100 kA). The estimated quantile is the mean of the bootstrap samples, and the error bounds are the maximum of the difference between the estimated mean quantile and the 97.5% and 2.5% quantiles of the bootstrap samples.

B Summary of January 2016

To explore the dataset and typical values, we analyzed all strikes in January of 2016, which consisted of roughly 1.8 million observations. About 66% of observations were cloud strikes and 34% were ground strikes. About 41% of observations were negative polarity and 59% were positive. The number of sensors measuring strikes varied from 2 to 48, with mean about 6, and appear heavy tailed (Figure 10).

Previous researchers have claimed that lightning peak strikes follow a log-normal distribution. We examined this assumption by plotting histograms of the base 10 logarithm of all peaks (in kA), positive peaks only, and negative peaks only (see Figure 11). We computed the Shapiro-Wilk test statistic for normality (the statistic takes values on the interval $(0, 1)$, and values close to zero indicate agreement with normality). All distributions are significantly non-normal. Interestingly, the negative peaks appear to have tails that are too light, while the positive strikes have a positive tail that is too heavy to be log-normally distributed.

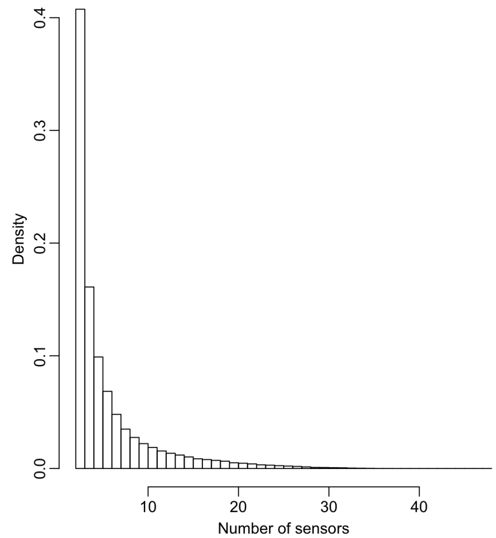


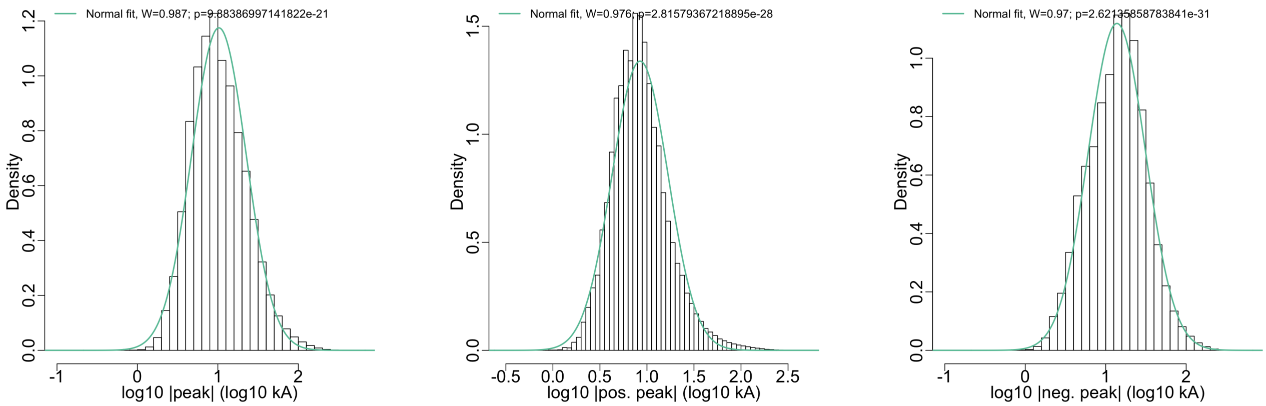
Figure 10: Histogram of number of sensors measuring each strike in January 2016.

We compared the absolute peak strike currents when separated by cloud/ground strike and polarity in Figure 12. Ground strikes are generally larger than cloud strikes, and positive strikes are generally larger than negative strikes. The effect of cloud vs. ground strike is greater than the effect of polarity. An ANOVA model of base 10 logarithm of absolute peak strike current against could/ground strike and polarity suggests that both effects are significant, as is the interaction of the factors ($p < 0.001$, $R^2 = 0.44$). Each subset of the absolute peak strike currents by cloud vs. ground and polarity was statistically significantly non-log-normal (Shapiro-Wilk, $p < 0.001$).

Table 2: Quantiles of peak current (kA), separated by polarity and cloud vs. ground strikes.

	95%	99%	99.9%	99.99%
All	40.50	82.80	170.60	270.24
+	28.70	65.40	158.18	256.86
-	51.31	97.60	183.70	284.94
Cloud	17.20	23.90	41.10	67.29
Ground	66.00	122.40	216.90	320.94
C+	16.90	22.20	30.50	52.01
C-	19.50	32.50	55.20	123.42
G+	90.40	157.00	256.52	365.66
G-	60.10	110.70	197.50	307.24

We see in 13 that peak current depends on the number of sensors measuring the peak,



All peaks Positive peaks Negative peaks

Figure 11: Logarithm of peak lightning strikes, separated by polarity and compared to normal distribution fit. Shapiro-Wilk test statistics and p-values are given in the legends.

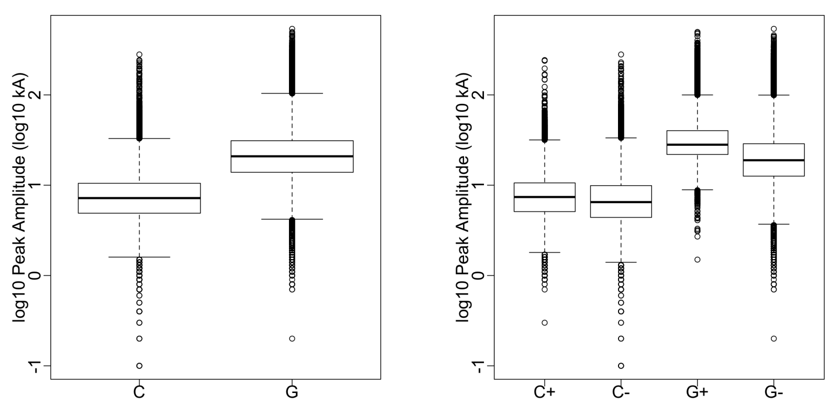


Figure 12: Logarithm of peak lightning strikes, separated by cloud/ground strike and polarity.

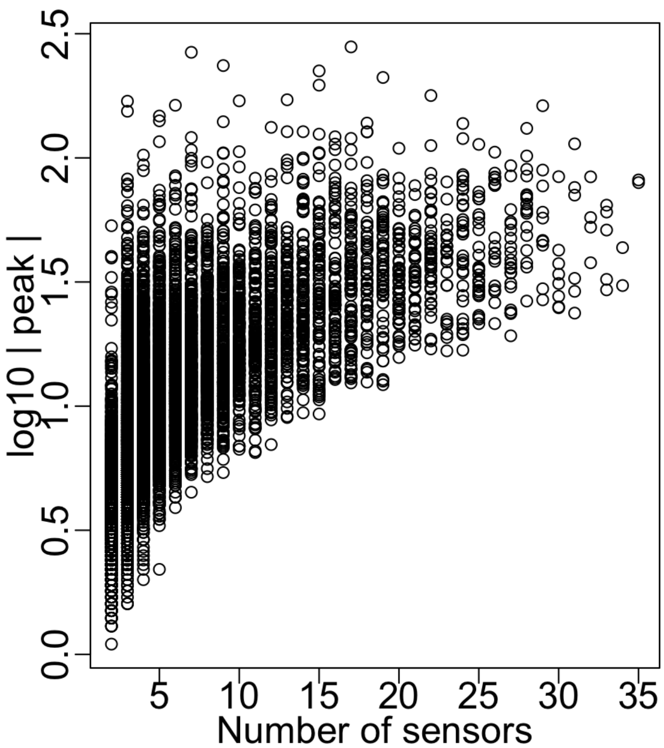


Figure 13: Absolute peak values as a function of the number of sensors measuring the peak.